now developed efficient plastic light emitters in a rainbow of different colors, setting the stage for full-color plastic video displays, computer screens, and televisions.

The new displays are "very impressive," says Yang Yang, a polymer display researcher at the University of California, Los Angeles. "They have combined light-emitting polymers with polysilicon thin-film transistors [TFTs]," he says. TFTs control the electrical current for each picture element, or pixel, in active matrix screens, such as those in today's laptop computers. Because light-emitting polymers are cheap to make and easy to apply over large surfaces, they open the door to making billboard-sized displays, especially if combined with easily printed polymer-based circuitry. This could help polymer devices claim a large portion of the display market, projected to be $45 billion a year by 2000.

Researchers have previously managed to incorporate light-emitting polymers into less advanced passive matrix displays, which send current to entire rows of pixels at once. But because these displays are slow to change images, they are generally good only for low-information content pictures such as text, rather than complex, fast-moving video images. To take the next step, CDT researchers teamed up with Seiko-Epson, a Japanese firm that makes the silicon-based circuitry for active matrix displays. Today's active matrix computer screens use a trio of filters at each pixel to filter out select colors of light shining through from a white backlight. The filtering is done by liquid-crystal molecules between two panes of glass. A voltage applied across pairs of electrodes, one on each pane, switches the liquid crystals from a transparent to a filtering state. The voltage is controlled by a tiny TFT printed on the glass at each pixel.

The new display does away with one of the glass panes and the liquid-crystal filters. On top of a single glass pane prepatterned with an array of TFTs, researchers spot down an array of transparent electrodes, each wired to its own TFT. This array is then coated with a light-emitting polymer known as poly(phenylene vinylene), or PPV, and an opaque electrode on the top. The array of tiny TFTs controls the current to each pixel. When a TFT turns on, the electrodes inject negatively charged electrons and their positively charged counterparts, called "holes," into the polymers. As the charges migrate toward the oppositely charged electrodes through the intervening polymer, some electrons and holes meet up and combine to give off photons of light, which shine through the transparent electrode and glass.

Creating a display that shines in a single color is quite an achievement, but getting to full-color polymer displays remains a major challenge. One hurdle is that different polymers are needed to emit light in different colors, and they come with a range of properties. For example, although it takes only a small electrical voltage to induce PPV to glow efficiently, the same can't be said for polymers that emit other colors. That's a big problem for displays, says Friend, as it can cause some colors to shine more brightly than others. Last spring, however, chemist Ed Woo of Dow Chemical in Midland, Michigan, reported discovering a new family of polymers that, with a bit of tinkering, can emit colors across the visible spectrum. At the Boston meeting, Friend reported that CDT researchers have used these polymers to make a variety of light-emitting diodes, all of which, it turns out, emit light with similar high efficiencies and at low voltages.

CDT and Dow have not revealed the exact chemical structure of their new polymers. They will say only that all are derivatives of polyfluorene, and each contains a chain of phenylene rings with a particular side group connected to neighboring pairs of rings. The researchers found that they can tune the color of light emitted from the polymer, from blue through to red, by simply changing the side groups on the polymer chain. Yang calls the new light emitters "a very important step forward for the field," because their near-uniform behavior will make it easier to make full-color displays.

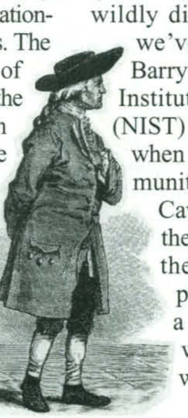
–ROBERT F. SERVICE

PHYSICS

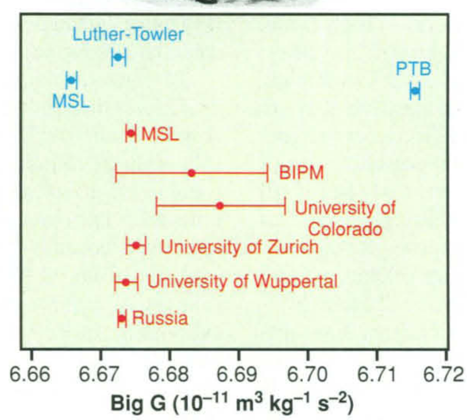
Gravity Measurements Close in on Big G

The precise strength of this pervasive force has proved surprisingly elusive, but conflicting results are finally giving way to a single answer

Two hundred years ago, in a stone house on the outskirts of London, Henry Cavendish weighed the world. By the light of a candle, he watched as a small lead barbell suspended by a fiber twisted minutely under the gravitational tug of two bowling ball–sized weights. The size of the twist revealed the strength of gravity between the two known masses, the barbell and the balls. Because Cavendish knew how strong Earth's tug was, he could then precisely pin down its mass.



The mass of the Earth is no longer a burning question, but the Cavendish experiment is legendary. The torsion balance is still one of the best ways to measure gravity's strength, a number called the gravitational constant, or Big G. G is perhaps the most elusive of all the fundamental quantities. While the charge of the electron is known to seven decimal places, physicists lose track of G after only the third. For some, that's an embarrassment. "It grates on me like a burr in the saddle," says Alvin Sanders, a physicist at the University of Virginia in Charlottesville.



Pulling together. New readings of G (red) are in rough agreement, hinting at an end to a quest that goes back to Henry Cavendish (*top*).

Over the past few decades, he and a handful of other physicists have dedicated themselves to measuring G more accurately. To their dismay, they've come up with wildly different values. "You might say we've had negative progress," says Barry Taylor, a physicist at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland. But when 45 members of the Big G community met last month* to honor the Cavendish anniversary and discuss the remarkable lack of progress over the last two centuries, they had a pleasant surprise. Six groups using a variety of techniques weighed in with new values of G, and they were all in rough agreement.

Because the results—one of which is reported on page 2230 of this issue—are preliminary and disagree with some older measurements, the G-men are cautious about declaring the case closed. But many suspect experimental finesse may finally be settling the long debate over the value of G. "The numbers are sort of converg-

CREDIT (TOP): CORBIS-BETTMAN

ing," says Tim Armstrong, a physicist at New Zealand's Measurement Standards Laboratory (MSL). Finally "a consensus is emerging."

Heavy lifting. Measuring gravity is harder than it might seem. Its relentless pull is apparent to anyone who has tried to shift a refrigerator or watched a rocket gun for the heavens, but when compared to other forces, gravity is unimaginably feeble. If gravity were as strong as the electric force that pulls oppositely charged things together, a bathroom scale would read out your weight in a number some 40 digits long. To accurately gauge gravity's tiny tug, most experiments have to be carefully isolated from electrical and seismic disturbances and performed in a vacuum to minimize the push of atoms in the air as they bounce off the test objects.

The going is also tough for another reason: No container can shield out the gravitational attraction of other objects. Riley Newman, a physicist at the University of California, Irvine, likes to tell the story of how his group once discovered a peculiar early morning wiggle in gravity's strength. After months of head-scratching, a graduate student leaving the lab at 3 a.m. was literally doused by the answer: The sprinkler system on the surrounding lawn, set on a regular clock, was soaking the ground with enough water to create an additional nearby mass, which skewed the morning readings. Newman says the group's new experiments will be done in an abandoned Nike antiaircraft missile bunker in Washington state, far from the lawns of suburban America.

What's the payoff for all the trouble? Very little. "Nobody gives a damn about Big G," says Clive Speake, a physicist at the University of Birmingham in England who organized the conference. One day, physicists hope to merge quantum mechanics and gravity, which might allow them to calculate what Big G should be. They could then test the theory by comparing the predicted G to the measured value. But for now, measuring it is a kind of sport—a Mount Everest of precision measurement. "You have to be an oddball to do this," Speake admits. Cavendish was no exception, he points out. A colleague once described the reclusive physicist as speaking fewer words than a Trappist monk.

The official value for G—chosen by an international panel in 1986—comes from a 1982 measurement by Gabe Luther, now at Los Alamos National Laboratory in New Mexico, and William Towler of the University of Virginia. Their setup was similar to Cavendish's: a tiny barbell hung from a long fiber made of quartz or tungsten. When disturbed, the barbell would rotate lazily back and forth about once every 6 minutes, driven by the fiber's resistance to twisting. When two huge tungsten balls were brought near, their gravitational tug on the barbell slowed the swing time by a split second. By measuring that difference, Luther and Towler pegged Big G with an estimated accuracy of better than a hundredth of a percent.

All was well until 1994, when heavyweights at the German standards lab, the PTB in Braunschweig, announced a value of G that was supposed to be just as accurate. It was, by all reckoning, a tour de force measurement. Instead of suspending test weights from a delicate fiber, they floated them on a layer of mercury. That allowed the researchers to use larger masses and generate a stronger pull. To everyone's shock, their value came out way above the Luther-Towler number—a full half-percent larger. Things got worse in 1995 when New Zealand's MSL came out with a number that significantly undercut the accepted value (see chart).

Some physicists in the standards community took the conflict as a challenge. After all, they'd measured time accurately enough to build clocks that slip by only a second every 100 million years. Not to be bested by gravity, many joined the effort to hunt down Big G. Worried that perhaps the traditional torsion balance might not be up to the task, many tried new techniques.

Turn signal. The gravitational pull of two large masses twists a barbell hanging in a torsion balance.

Weighing in. One of the more outlandish approaches reported at the conference came from a group including James Faller, a physicist at NIST in Boulder and the University of Colorado. Loosely speaking, the team dropped a weight through the hole of a large tungsten donut, then raised the donut above the release point and dropped the weight again. With the donut below, its gravitational tug made the weight fall faster. When the donut was overhead, it slowed the object's descent by a hair. From the tiny difference between the two drop times, the team teased out the value for G they report in this issue.

A group at the University of Zurich also scrapped the torsion idea and suspended small masses, a kilogram each, from a precision scale. By moving other large masses above and below the kilograms, the researchers could change their effective weight and measure G. In work published in a recent *Physical Review Letters*, the large masses were vats of water. Now they've gotten their hands on a few bathtubs worth of mercury, which pulls on the test masses with a force equivalent to that of 2000 tons of water, making G easier to measure.

Researchers at the University of Wuppertal in Germany are lugging around huge masses as part of a different scheme, which relies on two pendulums hung side by side. When the team wheels in a half-ton mass on either side, the tug of the masses pulls the pendulums apart slightly—"by about the width of an atom," says team member Hinrich Meyer. By bouncing microwaves between the bobs, he and his colleagues can size up the gap and sift out G.

The torsion balance hasn't disappeared from the scene, however. Clive Speake, working with Terry Quinn, a physicist at the international standards lab, the BIPM near Paris, and others announced a new measurement made with a torsion balance in which the thin fiber was replaced by a broad strip. The strip could support heavier masses, and it eliminated problems that can plague a fiber. When a fiber twists quickly, many of its atoms become temporarily dislocated. This effect changes how strongly the fiber resists twisting, which can throw off the measurement. But a strip resists twisting by wrapping and shortening, which is entirely reversible. A Russian group, led by Oleg Karagioz, also submitted new results using a more traditional torsion balance.

The new results all point to a value of G hovering just above the Luther-Towler number. And one of the old outlying measurements was also brought within the fold at the meeting. The New Zealand group revealed that they had uncovered a simple but grave error in their old measurement. They'd forgotten to include the thickness of the walls of the cylinder they'd hung from their torsion fiber when they calculated the cylinder's moment of inertia, which affects how fast it reacts to the pull of a nearby mass. The slip was "embarrassing," Armstrong says. But the group has now remeasured G, and "we believe our new numbers are right."

That leaves one dangling thread—the far-out results of the PTB. "Nobody understands it," says Meyer. "They must have made an unbelievable mistake, but we cannot find it." But if the tentative consensus on big G strengthens, says Terry Quinn, "we may just have to throw the PTB result out." Already physicists are hatching plans for new measurements. "I now own a 1050-pound tungsten [donut]," says NIST's Faller. "What else am I supposed to do with it?"

–DAVID KESTENBAUM

* "The Gravitational Constant: Theory and Experiment 200 Years After Cavendish," 23 to 24 November, Institute of Physics, London.